HOLOCENE ROCKWALL RETREAT IN SVALBARD: A TRIPLE-RATE EVOLUTION

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ABSTRACT

Volumetric calculations of slope deposits, direct measurements of rockwall retreat and chronological control based on lichenometry provide a wide range of rockwall retreat rates in Svalbard (0–1580 mm ka^{-1}) that appears consistent with previous evaluations from other Arctic areas. In northwest and central Spitsbergen (79°N), a triple-rate rockwall retreat is suggested for the last two millennia: very slow biogenic flaking (2 mm ka^{-1}), moderate retreat due to frost shattering (100 ka^{-1}) and rapid retreat associated with post-glacial stress relaxation (*c.* 1000 mm ka^{-1}). Examination of the distribution of various processes indicates that the Holocene retreat of most rockwalls has not exceeded one or two metres. Bedrock conditions appear to be the main control on retreat rates. The massiveness of igneous and metamorphic outcrops, widespread in Arctic shield areas, largely accounts for the slowness of rockwall retreat, which on these lithologies is primarily due to chemical and biological processes. More rapid rates are usually associated with stress relaxation following glacial surges or with local frost susceptibility of bedrock, often where faulting has induced high joint density. At such sites, rockwall retreat rates are of the same order of magnitude as those reported from Alpine areas (1000–3000 mm ka^{-1}) where both bedrock weakening due to tectonic stresses and the greater height of steep rockwalls account for the more rapid rockwall retreat rate. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Recent reviews of rockwall retreat rates around the world emphasize the scarcity and the disparity of estimates from Arctic areas (e.g. Ballantyne and Harris, 1994; Goudie, 1995). The data set presented on Table I shows that Holocene rockwall retreat rates, expressed in millimetres per thousand years (mm ka^{-1}), vary from 0 to 1500 according to the authors and locations (from Yukon to north Finland). As the methods of calculation and the reference period (9 ka on average) are very similar, the reason for the disparity of retreat rates most probably comes from the variety of climatic, topographic and geological conditions. Unfortunately, the high number of parameters prevents identification of the prominent controlling factors. Also, most previous estimates are not associated with a specific geomorphological process but refer to a combination of processes involved in Holocene rockwall retreat.

In Svalbard, where pioneer studies were performed by Rapp (1960a) and Jahn (1961), a five-year research project was carried out by André (1993) in both central and northwestern Spitsbergen, the main island of the archipelago (Figure 1). Fifteen rockwalls were selected which had all obviously retreated during the two last millennia under the prominent – if not exclusive – action of one of the following processes: stress relaxation, frost shattering, biological flaking. Moreover, in the same area, the recent calibration of a lichen growth curve by Werner (1990) provided chronological control of the late Holocene rockwall retreat. Such suitable conditions make it possible to provide new data that are significant in so far as they arise from the same study area and are associated with well identified geomorphological processes governed by specific bedrock and glacier conditions.

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Table I. Holocene rockwall retreat rates in arctic environments: previous estimates

Location	Lithology	Average retreat period	Rockwall retreat rates ($mm\,ka^{-1}$)			Source
		(a)	Minimum	Mean	Maximum	
Northern Finland	Various (schist, dolomite, quartzite, granite)	9500	40		940	Söderman (1980)
Swedish Lappland and north Norway	Amphibolite and granite	9000	0		900	Rapp and Rudberg (1964)
Central Spitsbergen (Mt Templet, Bjonahamna)	Limestone	10000	340		500	Rapp (1960a)
W Greenland (Disko Island)	Volcanics (mostly basalt)	7000	500		1500	Frich and Brandt (1985)
Ellesmere Island (Arctic Canada)	Limestone	8000	500		1300	Souchez (1971)
Yukon Territory (Canada)	Igneous (syenite and diabase)	10000	7	18	30	Gray (1972)
Yukon Territory (Canada)	Metasedimentary (slate, dolomite, quartzite)	10000	20	70	170	Gray (1972)
Alaska	Granite	*c*. 1000	5		20	Hall and Otte (1990)
All arctic sites	Various	9000	0		1500	

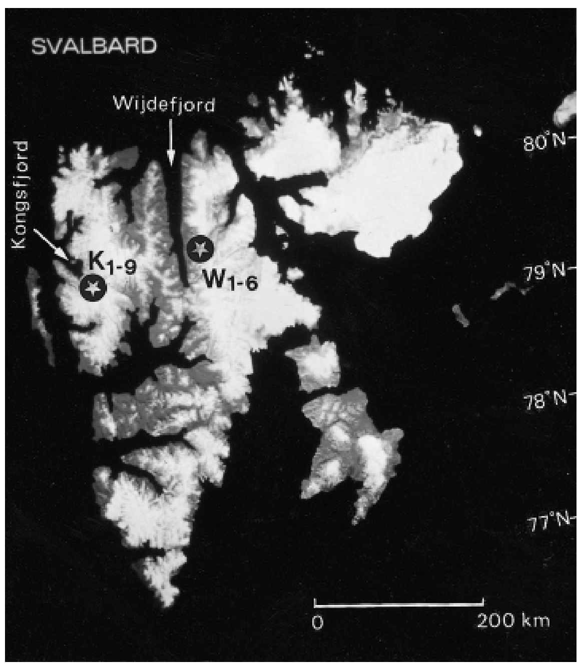

Figure 1. Location of the two study areas in northwest and central Spitsbergen (K = Kongsfjord, W = Wijdefjord). Landsat image provided by R. S. Sletten

So the aims of the present paper are twofold: (1) to provide new estimates of rockwall retreat rates for Arctic Scandinavia and to assess the representativeness of these values; (2) to compare these new estimates with previous evaluations from Arctic and Alpine areas at various timescales within the Holocene and to identify the prominent controlling factors of rockwall retreat.

STUDY AREA

Geomorphological investigations were carried out on Spitsbergen (79°N, 12–16°E), halfway between the Arctic circle and of the North pole, in two study areas: Kongsfjord on the northwest coast, and Wijdefjord in central Spitsbergen (Figure 1). The northwestern study area is located in a polar oceanic environment whose main attributes are a mean annual temperature of −6°C, minimum winter temperatures of −33°C, an annual precipitation of 400 mm and equilibrium line altitudes around 300 m. Central Spitsbergen is more continental, with minimum winter temperatures of −44°C, precipitation less than 200 mm and equilibrium lines around 800 m.

The Svalbard archipelago experienced the same Holocene climate fluctuations as the rest of Arctic Scandinavia. Radiocardon dating of whale bones and driftwood indicates that deglaciation of the investigated fjords occurred at the end of the Weichselian glaciation, i.e. between 13 000 and 10 000 years BP (e.g. Corbel, 1966; Salvigsen, 1977; Forman and Miller, 1984). During the Holocene, the 'Atlantic climatic optimum' (from about 6500 to 5000 years BP according to Salvigsen (1978) was followed by a colder period (*c.* 3500–2000 years BP) characterized by rock glacier formation (André, 1994). Then, the mild 'Viking second optimum' occurred between 1150 and 750 years BP and was followed by the 'Little Ice Age' Neoglacial stadial (*c.* 750–50 years BP according to Grosswald (1967) and Baranowski (1977). The contemporary climate amelioration started at the end of the last century and culminated in the late 1930s.

Nowadays, Spitsbergen is still extensively glaciated, particularly along the northwest coast. In the Kongsfjord area, nine study sites were selected (K1 to K9 in Figures 2 and 4A), of which seven are located at the

Figure 2. Oblique view of the Kongsfjord study area (aerial photograph 078 – 1936, Norsk Polarinstitutt, Oslo)

head of the fjord, on the Ossian Sarsfjellet nunatak. This low bedrock island (362 m a.s.l.) is episodically submerged by surging ice of eastern origin. The last surge of the marine-calving Kongsbreen happened in 1948 but affected only the southern tip of the nunatak, which is covered by fresh reddish till mainly consisting of granite and Devonian sandstone. The study sites are located a little north of this recently ice-covered area, along a small transverse valley whose walls consist of a series of vertical rockwall elements (K1 to K7, Figure 4A), up to 50 m high, cut into massive Precambrian quartzite and quartzophyllite (joint spacing up to 3 m). Behind the slightly overhanging rockwalls, the broad and deep joints, parallel to the ice flow, suggest that chaotic boulder accumulations downslope result mainly from post-glacial stress relaxation (see below, Figures 5A, 11 and 12). In the same northwestern coastal area, two additional sites (K8 and K9) were investigated south of Kongsfjord, where a north-facing rocky slope, reaching to 767 m a.s.l. (Grönlietpynten), offers suitable conditions for rockwall rate estimates thanks to the presence of interbedded densely fissured and frost-shattered quartzite layers within a stable Precambrian mica schist (see below, Figure 5B).

In central Spitsbergen, since the Wijdefjord deglaciation (*c.* 12 ka BP according to Mann, personal communication based on radiocarbon dating), weathering has been operating on the adjacent rockwalls. Study sites W1 to W6 are located on the eastern side of Wijdefjord where a rocky slope, 400 m high, slopes gently (25–40°) towards the fjord (Figures 3 and 4B). The slope gradient is strictly controlled by the dip of Precambrian amphibolite slabs, 50 cm thick, whose surface is subjected to widespread biogenic flaking and granular disintegration below a dense lichen cover. The thinner tip of the slabs is the only part of the outcrops to be affected by frost shattering (see below, Figures 8 to 10). Amphibolite slabs, whose joint spacing is 40 cm, appear as discontinuous rockwall elements as they are partly covered with till material.

METHODS

In the 15 study sites, whose main attributes are summarized in Table II, various methods were used in order to calculate the global retreat of the investigated rockwall elements and to assess the duration of the retreat period.

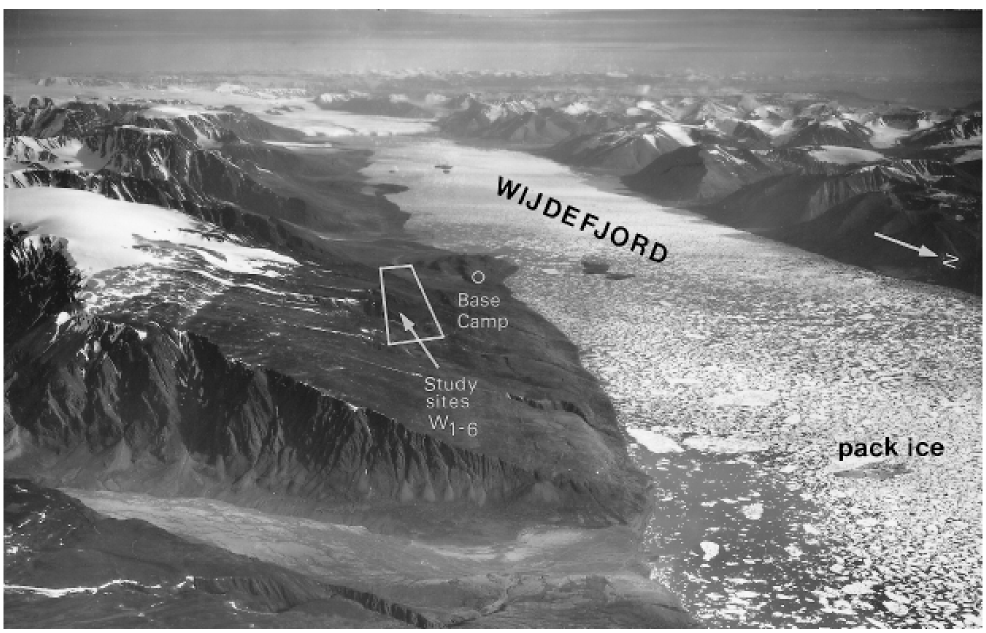

Figure 3. Oblique view of the Wijdefjord study area (aerial photograph S36 – 11-5-2, Norsk Polarinstitutt, Oslo)

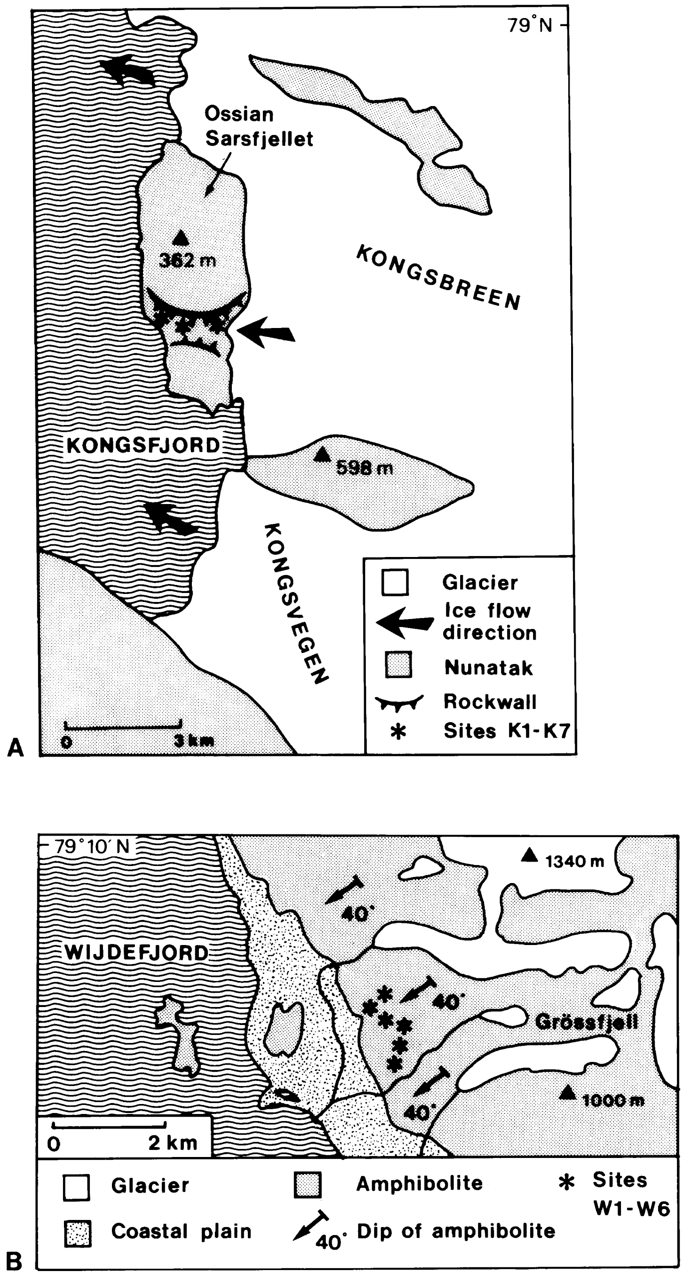

Figure 4. Location maps. (A) Study sites K1–K7 on the Ossian Sarsfjellet nunatak in the Kongsfjord area. (B) Study sites W1–W6 on the east side of Wijdefjord

Rockwall retreat evaluation

In previous studies carried out in Greenland and northern Scandinavia (Rapp, 1960a; Söderman, 1980; Frich and Brandt, 1985), post-glacial rockwall retreat rates have been inferred from the calculation of talus cone volumes based on theodolite readings, slope angle measurements and computation following the Lehmann model (Carson and Kirkby, 1972, pp. 142–144) for rectilinear talus slopes. Such a volumetric approach was used by the author on the Ossian Sarsfjellet nunatak where seven greenish boulder accumulations, easy to distinguish

Table II. Characteristics of study sites

Study area	Study sites	Glacier conditions	Characteristics of investigated rockwalls				Weathering processes involved in rockwall retreat
			Aspect	Slope gradient	Lithology	Joint spacing (cm)	
Wijdefjord 79°N (east side of the fjord)	W1–W6	Deglaciated valley	W	40°	amphibolite	40	Biogenic flaking (widespread) frost shattering (locally)
Kongsfjord 79°N, NW coast							
Ossian Sarsfjellet	K1–K7	Low nunatak exposed to surges	S	90° (overhanging)	quartzite	200	Stress relaxation
Grönlietpynten	K8–K9	Deglaciated area	N	50°	quartzite	10	Frost shattering

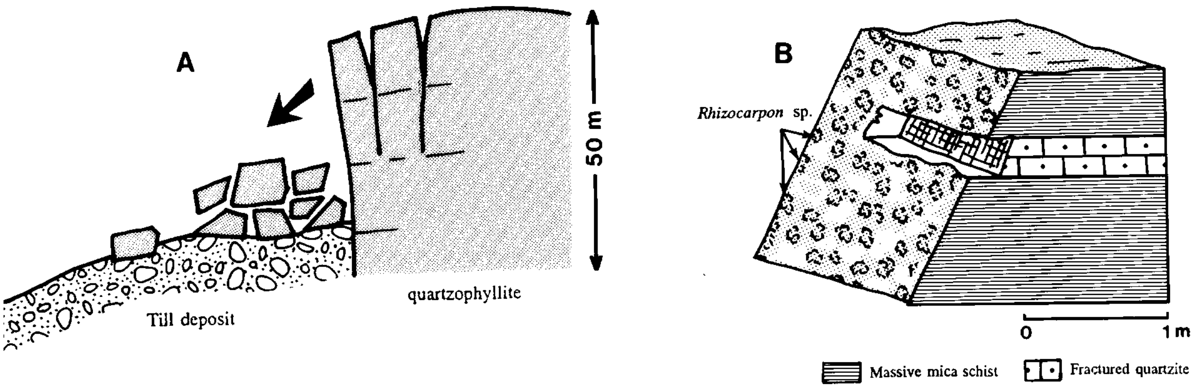

Figure 5. Methods of evaluation of rockwall retreat. (A) Calculation of compact volumes of talus accumulations. (B) Direct measurement of retreating layers in a stable rockwall

from the underlying reddish till deposit, are associated with distinct rockwall elements (Figure 5A). Field measurements were made with a string ‘topofil’ used by speleologists, which is easier to handle than a steel measuring tape. The surface area of the rockwall element delivering debris was calculated and the compact volume of debris accumulated downslope was evaluated. Aside from the boulder accumulation itself, individual quartzite elements embedded in till material, that underwent limited gelifluction, were also taken into account. Porosity of talus deposits was assumed to average 33 per cent, which might lead to a slight overestimate (by *c.* 10 per cent of the compact volume owing to the chaotic arrangement of boulders and to the incorporation of granite erratics derived from the top of the retreating rockwall (see below, Figure 12). Finally, the debris volume of each accumulation was related to the rockwall surface area to estimate the overall rockwall retreat.

At other sites, direct retreat measurements were made by using the method initiated by Dahl (1967) and continued by André (1995), based on ice-polished quartz veins, to evaluate the post-glacial lowering of glacial surfaces in north Scandinavia. On Spitsbergen, this method was applied to eight sites (K8 and K9 and W1–W6) that offered suitable conditions. A series of smooth rockwall elements, covered with circular lichen thalli, were used as reference surfaces, both in amphibolite and massive mica schist. The local existence of retreating layers interbedded in those stable walls facilitated the direct measurement of the retreat (Figure 5B). Limitations of the method come from the scarcity and the limited extent (3–20 m^2) of rockwall elements presenting such suitable conditions.

Figure 6. *Rhizocarpon* section *Superficiale* (Runem.) Thoms. used in lichenometry. The scale is 3 cm long

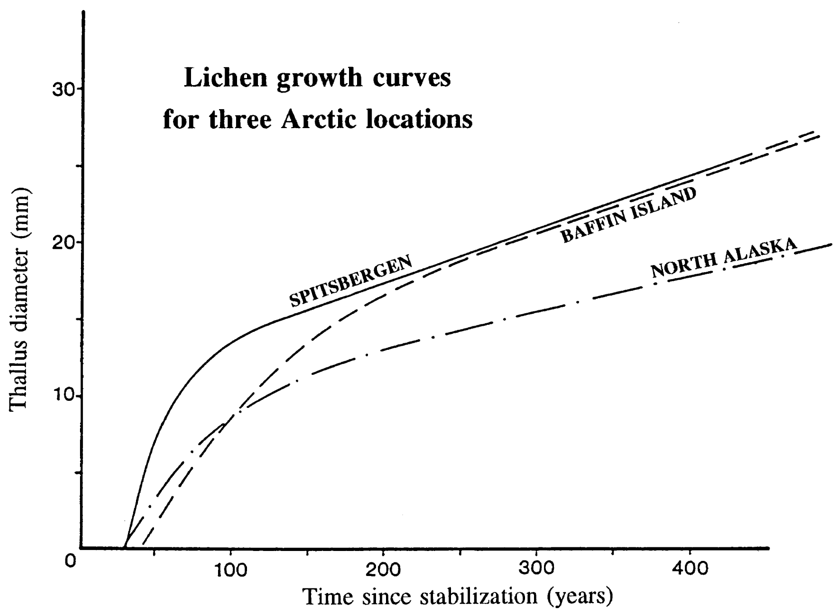

Figure 7. Growth curves of yellow *Rhizocarpon* in northwest Spitsbergen, Baffin Island and North Alaska (from Werner, personal communication, 1988. See also Werner, 1990)

Chronological control

Chronological control of the estimated rockwall retreat was based on the recent development of lichenometry in the Svalbard archipelago, where yellow *Rhizocarpon* (Figure 6) are widespread. These crustose lichens are known to live for up to 9000 years in the Arctic (Miller and Andrews, 1972). On Spitsbergen, a growth curve was established by Werner (1990) based on various dated control points such as

monuments and whaling graves (Figure 7). It allowed the author to make extensive use of lichenometric methods, resulting in the measurement of 13 000 *Rhizocarpon* thalli located at 320 sites including the 15 sites investigated for rockwall retreat studies (André, 1993). Sampling procedures, based on Lock *et al*. (1979), can be summarized as follows. Identification of *Rhizocarpon* sections (*Geographicum* and *Superficiale*) was based on chemical tests and microscopic examination of 300 samples. The *Alpicola* section, which is known to grow 10 per cent faster than the *Geographicum* group (Innes, 1985) was eliminated as far as possible. The diameter of circular thalli was measured at the rockwall surface (Figure 6) and the average diameter of the five largest thalli was calculated where sampling areas reached 100 m^2, whereas the single largest thallus was recorded at study sites less than 20 m^2.

The duration of rockwall retreat inferred from lichenometric surveys, which coincides on the Ossian Sarsfjellet nunatak with the time elapsed since local deglaciation, ranges from site to site between one and two millennia. Such a duration raises a methodological problem for the lichen growth curve, established on Spitsbergen by Werner (1990), is only controlled for the last four centuries (Figure 7). Fortunately, the *Rhizocarpon* growth rate is known to be characterized by two stages: first, a fast-growing period (15 to 30 mm per century in the Arctic) which lasts two centuries on average; then, a slow-growing period (3 mm per century in the Arctic) which remains the same during millennia whatever the climate fluctuations (e.g. Miller and Andrews, 1972; Calkin and Ellis, 1980). So Werner's curve, which includes the fast-growing period and the beginning of the slow-growing period, allows the extrapolation of data up to two millennia, based on the correspondence of the Spitsbergen curve with the long-term controlled curve established by Miller and Andrews (1972) on Baffin Island (Figure 7).

Chronological control appears very approximate and the number of sites investigated (only 15) rather low, but it is quite clear from previous studies that sites suitable for such evaluations are seldom found. The post-glacial retreat rates proposed by Rapp (1960a) for the Bjonahamna site in central Spitsbergen are inferred from the study of four talus cones, and Rapp himself points out the uncertainty of chronological control, as does Söderman (1980), who extrapolated chronological data for northern Finland from lichen growth curves established in Swedish Lappland. It is quite clear from previous and current studies that estimates like those proposed here should be considered as rough orders of magnitude due to the limitations of the methods.

RESULTS

Compilation of results from the 15 study sites suggests the existence of a triple-rate evolution connected with three main processes (biogenic flaking, frost shattering and stress relaxation) involved in Holocene rockwall retreat.

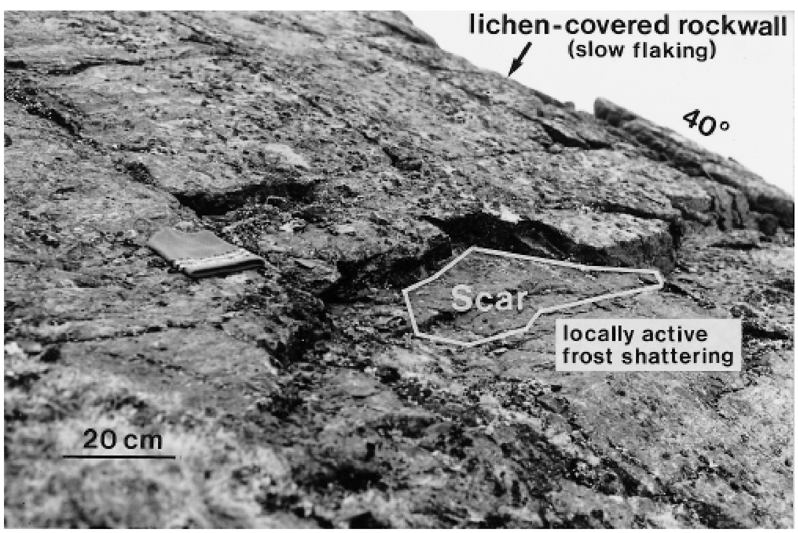

Figure 8. Amphibolite slab submitted to widespread biogenic flaking and localized frost shattering (east side of Wijdefjord). See also Figure 10

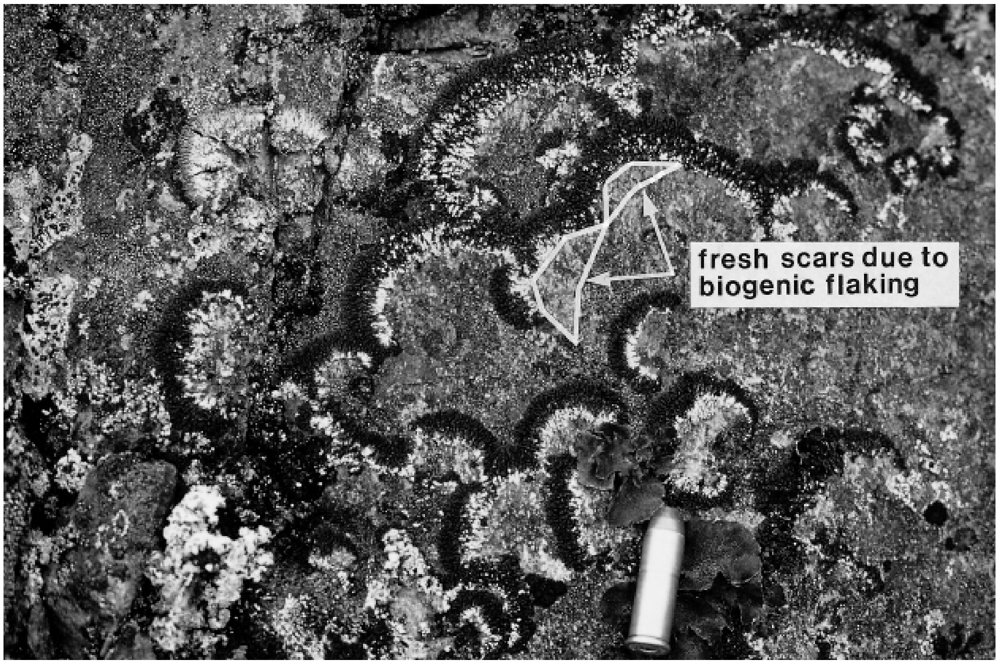

Figure 9. Remaining lichen rings of decayed *Parmelia* thalli with fresh scars due to biogenic flaking affecting amphibolite and gneiss rockwalls on the east side of Wijdefjord

Table III. Tentative estimates of rockwall retreat rates due to biogenic flaking in amphibolite (Wijdefjord area, central Spitsbergen)

Study site (Wijdefjord)	Maximum diameter of *Rhizocarpon* (mm)	Average retreat period (a)	Rockwall retreat, min.–max. (mm)	Average retreat rate due to biogenic flaking (mm ka^{-1})
W1	55	1540	0–6	0–3·9
W2	47	1240	0–5	0–4·0
W3	38	920	0–5	0–5·4
W4	42	1030	0–4	0–3·9
W5	64	1880	0–8	0–4·2
W6	44	1120	0–4	0–3·6
All sites	48	1290	0–5	0–4·2 (mean 2·1)

Slow biogenic flaking

Amphibolite and gneiss mountain walls of Spitsbergen are commonly colonized by a lichen community dominated by *Rhizocarpon* section *Geographicum, Pseudephebe minuscula* and various species of *Parmelia* and *Umbilicaria* (Figure 8). The decay of lichen thalli leaves fresh scars of newly exposed rock surface, which correspond to the removal of flakes 1 to 6 mm thick. Such scars, 3 to 400 cm^2 in area, are either circular or crescent-shaped, depending on the pattern of lichen thalli involved in rockwall weathering (Figure 9). On the Wijdefjord amphibolite, where chronological control is provided by yellow *Rhizocarpon* colonizing the 'primitive' rockwall surface, tentative retreat rates corresponding to the scars range from 1 to 4 mm ka^{-1} (Table III). The average rate represents the removal of only 2 mm of rock material during the last millennium. Rockwall retreat rates may be even slower if one takes into account the fact that the *Rhizocarpon* thalli are preserved everywhere, which means that the rockwall has not retreated at all since 1000 to 2000 years BP. Rockwall stability might even have lasted for at least three millennia on massive quartz-cemented Carboniferous sandstone walls of the northwest coast, as these display well-preserved circular thalli reaching up to 100 mm (André, 1996a). At one site, the largest *Rhizocarpon* thallus ever observed by the author in

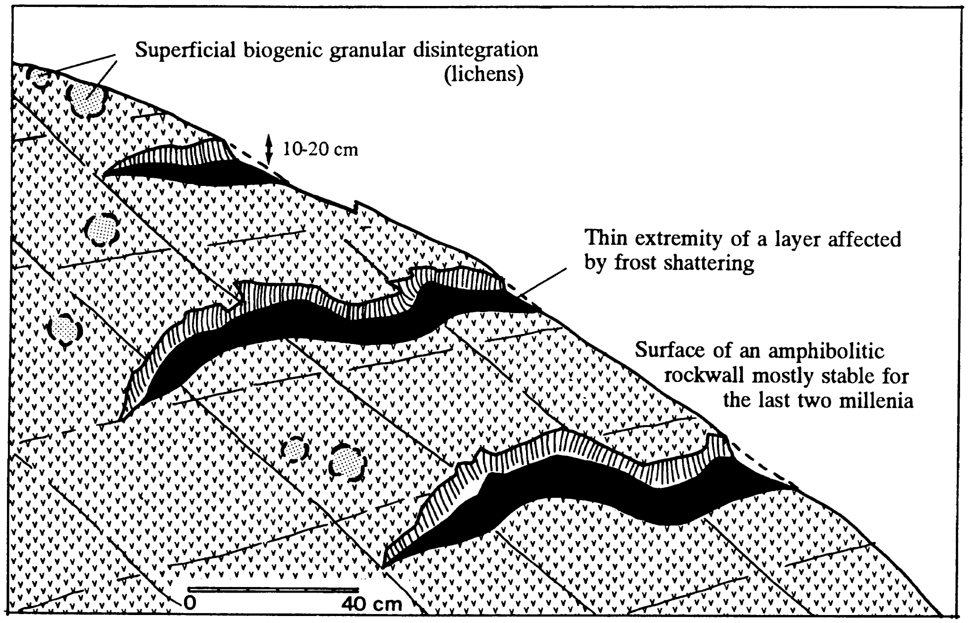

Figure 10. Smooth amphibolite rockwall exposed to widespread biogenic flaking. Fresh scars of lichen-free dark amphibolite (in black) coincide with the thinner extremity of the amphibolite slabs which is susceptible to frost shattering. See also Figure 8

Svalbard (200 mm in diameter but decayed in the middle) was found, which suggests the possibility of a longer rockwall stability period (5000 years or so).

Moderate retreat due to frost shattering

Whereas amphibolite rockwalls located on the east side of Wijdeford are mostly subject to slow, pellicular biogenic flaking, the thinner tip of amphibolite slabs (which represents 5 per cent of the surface area of the outcrops) is locally affected by frost shattering (Figures 8 and 10). In such locations, found at six study sites, tentative retreat rates range from 30 to 100 mm ka^{-1} and average 70 mm ka^{-1}, equivalent to the removal of a 7 cm thick amphibolite layer during the last millennium (Table IV, sites W1–W6).

Table IV. Tentative estimates of rockwall retreat rates due to frost weathering in amphibolite (Wijdefjord) and quartzite (Kongsfjord)

Study sites	Maximum diameter of *Rhizocarpon* (mm)	Average retreat period (a)	Rockwall retreat (mm)	Average retreat rate due to frost shattering (mm ka^{-1})
W1	55	1540	80–130	50–80
W2	47	1240	10–120	8–90
W3	38	920	50–130	50–140
W4	42	1030	20–110	20–110
W5	64	1880	240	130
W6	44	1120	40–100	30–90
All sites	48	1290	40–140	30–110 (mean 70)
K8	63	1810	200	110
K9	50	1350	300	220
Both sites	56	1580	250	160

A similar order of magnitude was obtained for the highly fissured quartzite layers in rockwalls in the northwest coast, which provide evidence for active retreat. In contrast to most of the massive gneiss and amphibolite rockwalls that are densely vegetated (lichen cover: 50–75 per cent) with mosses filling cracks, quartzite rockwalls display open joints, 1 to 10 mm wide, and are free of vegetation except for some fast-growing nitrophilous species, like *Lecanora melanophthalma* and *Xanthoria elegans*. Only two sites, where retreating quartzite layers are interbedded in stable rockwalls (see Figure 5B), provided chronological control and allowed tentative evaluation. Retreat rates at such sites average 150 mm ka^{-1} and therefore correspond to the removal of 15 cm of compact quartzite during the last millennium (Table IV, sites K8 and K9). Such rates can appear high compared to the very low rates attributed to biogenic flaking, but they are modest in comparison with the rates associated with post-glacial stress relaxation, as outlined below.

Rapid retreat associated with post-glacial stress relaxation

On the Ossian Sarsfjellet nunatak (NW Spitsbergen), lichen diameters were measured both on the ice-polished outcrops dotted with erratics over the top of rockwalls and on debris accumulations at the rockwall bottom. These slope deposits clearly result from post-glacial stress relaxation as suggested by the deep and widely opened joints (up to 1·20 m) running paralled to the cliff face and to the former ice flow direction (Figures 11 and 12). As can be seen on Table V, there is a good coincidence of diameters measured upslope and downslope (Figure 11), even if values from the top outcrops are slightly higher than those from the boulder accumulations due to the more extensive rocky surface of the former offering better conditions for lichen growth. Tentative assessments obtained at seven sites (K1–K7) providing lichenometric chronological control are presented in Table V. Retreat rates at these sites range from 100 to 1580 mm ka^{-1} and average 700 mm ka^{-1}. Rockwall retreat rates associated with stress relaxation mechanisms are therefore the highest ever measured on Svalbard.

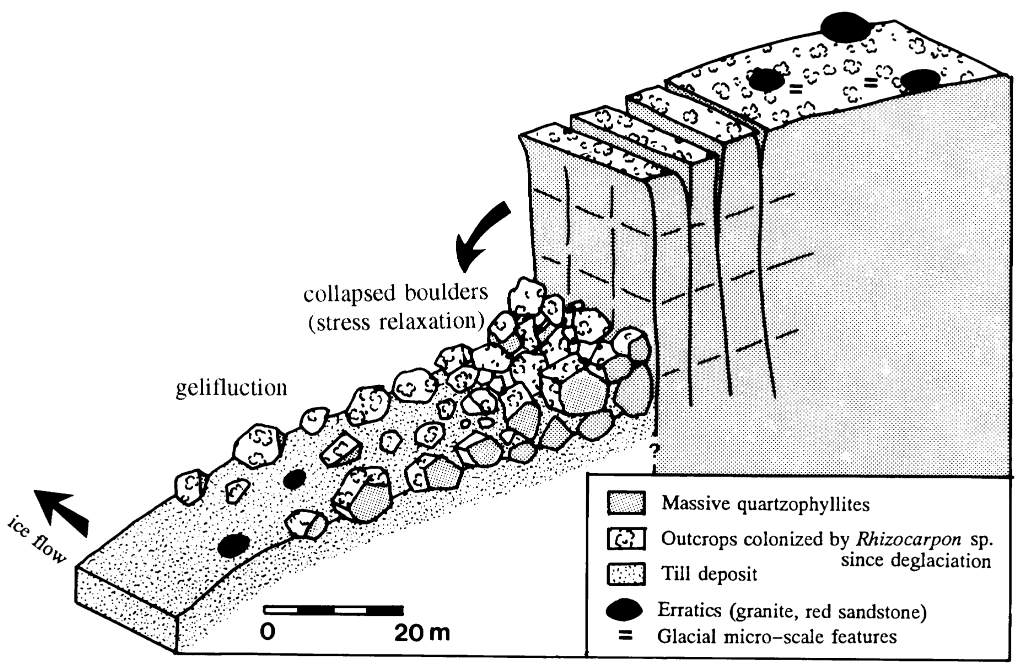

Figure 11. Overhanging quartzite rockwall affected by stress relaxation following glacial surges of Kongsbreen (Ossian Sarsfjellet nunatak, Kongsfjord area)

Figure 12. Close-up view of an open joint at the top of an overhanging rockwall parallel to the past ice flow. Ossian Sarsfjellet nunatak (gun for scale on the right). Kongsfjord and Bröggerpeninsula in the background

Table V. Tentative estimates of rockwall retreat rates due to stress relaxation in quartzite (Ossian Sarsfjellet nunatak, Kongsfjord area)

Study site (Kongsfjord)	Evaluation of rockwall retreat			Approximate retreat period			Rockwall retreat rate due to stress relaxation (mm ka^{-1})	
	Rockwall surface area (m^2)	Accumulation compact volume (m^3)	Rockwall retreat (m)	*Rhizocarpon* maximum diameter (mm) on debris accumulation	*Rhizocarpon* maximum diameter (mm) on top of rockwall	Retreat period (a)	Min.–max.	Mean
K1	420	222	0·53	32	33	740–770	690–720	700
K2	480	67	0·14	45	51	1180–1380	100–120	110
K3	575	232	0·40	54	63	1500–1810	220–270	250
K4	225	181	0·80	54	63	1500–1810	440–530	500
K5	550	571	1·04	57	59	1590–1650	630–650	640
K6	84	207	2·46	63	64	1810–1840	1340–1360	1350
K7	40	107	2·68	60	64	1700–1840	1460–1580	1520
All sites	340	230	1·15	52	57	1430–1590	100–1580	720

INTERPRETATION AND DISCUSSION OF RESULTS

Controlling factors of this triple-rate evolution

Along valleys that experienced early deglaciation and on rockwalls adjoining thin and slow-moving valley glaciers, field observations and measurements provide evidence for the pronounced influence of jointing on rockwall retreat rates: the denser the joint spacing, the faster the retreat. This is particularly evident with quartzites that display a joint spacing of 10 cm or less and are undergoing active retreat, locally of as much as 200 mm ka^{-1}. In contrast, massive rockwalls in gneiss and amphibolite with a joint spacing of 0·5 to 2·0 m and a very low porosity (0·7 to 2·0 per cent) appear very stable: their average retreat rate, mainly due to pellicular biogenic flaking and granular disintegration is tentatively evaluated for the amphibolite at only 2 mm ka^{-1}, i.e. two orders of magnitude less than retreat rates attributed to quartzite frost shattering. It must be added that apart from joints, other structural discontinuities, such as foliation planes, can influence rockwall retreat: the attack of the thinner tip of amphibolite slabs by frost shattering (Figure 10) provides a good example of such a control.

In northwest Spitsbergen, the prominent role of jointing has been previously inferred by the author from assessment of present-day retreat rates based on debris accretion on annual snowcover (André, 1990). During

the 1983–1985 observation period, a smooth and steep gneiss cirque wall, covered with slow-growing lichens, experienced a very low retreat rate (0·007 mm a^{-1}). In contrast, a mica schist and quartzite cirque wall dissected by wide chutes associated with transverse faults underwent much more rapid retreat (0·16 mm a^{-1}). However, the striking similarity of long-term and short-term retreat rates might be partly coincidental, at least for quartzite rockwalls: long-term rates apply to the direct attack of free faces by frost shattering (see Figure 5B), while short-term rates correspond to the impact of present-day avalanche activity that displaces frost-weathered clasts whose lichen cover shows that they partly formed at the end of the Little Ice Age (*Rhizocarpon* of 10 mm diameter). Nevertheless, the convergence of results is interesting in so far as it confirms the strong influence exerted by the tectonic pattern and especially the joint spacing on the rate of rockwall retreat.

In areas submitted to episodic surges of marine-calving glaciers, glacial dynamics surpass bedrock conditions as a major control of rockwall retreat by inducing stress relaxation mechanisms. On the Ossian Sarsfjellet nunatak (see Figures 2 and 4A), a very high retreat rate – almost 1000 mm ka^{-1} on average – is systematically associated with sites affected by post-glacial stress relaxation. Elsewhere, the very massive quartzite and quartzophyllite rockwalls do not seem to have retreated at all, for their 3 m joint spacing makes them unsusceptible to frost weathering as demonstrated by the lack of debris at the foot of cliffs aligned across the former ice flow. On the contrary, the effect of vigorous advances, like surges, in accelerating rockwall retreat rates seems quite clear on rockwall elements parallel to the former ice flow direction.

Representativeness of study sites

Assessing the representativeness of the study areas and consequently the relative impact of the three main processes involved in rockwall retreat is very difficult. What is inferred from field investigations is that slow, pellicular biogenic disintegration probably surpasses frost shattering in central Spitsbergen, where massive Precambrian gneiss and amphibolite outcrops are widespread. In contrast, the west coast, which belongs to the 'Spitsbergen Fracture Zone', displays numerous quartzite, mica schist and limestone rockwalls that are susceptible to frost shattering and even, for soft and porous limestone, to frost bursting. As for stress relaxation mechanisms, these were clearly identified only on the Ossian Sarsfjellet nunatak on the basis of the distribution of chaotic blocky debris accumulations at the bottom of overhanging walls with open joints running parallel to the former direction of glacier movement. If this process is associated with surging glaciers, as suggested above, it might be operating in various locations, for surging is quite a common form of glacier behaviour in Svalbard, especially for marine-calving glaciers (Liestøl, 1969). Indeed, the reason for the scarcity of field evidence for stress relaxation mechanisms might be that it is difficult to distinguish the effects of this process from those of frost shattering in densely jointed bedrock that yields relatively small-sized debris of uncertain origin.

Table VI. Summary of results: the triple-rate Holocene rockwall retreat on Spitsbergen

Process	Lithology	Location	Rockwall retreat rates (mm ka^{-1})	
			Min.–max.	Mean
Biogenic flaking	Amphibolite	Wijdefjord, 79°N	0–4	2
Frost shattering	Amphibolite	Wijdefjord, 79°N	30–110	70
Frost shattering	Quartzite	Kongsfjord, 79°N	110–220	160
Post-glacial stress relaxation	Quartzite	Kongsfjord, 79°N (Ossian Sarsfjellet nunatak)	100–1580	700

COMPARISON WITH PREVIOUS EVALUATIONS FROM POLAR AND ALPINE AREAS

The wide range of Holocene rockwall retreat rates obtained by the author in Svalbard and summarized in Table VI (0–1580 mm ka^{-1}) is very similar to the range of previous estimates for Arctic areas (0–1500 mm ka^{-1}) presented in Table I. Even though the highest rates are similar to those calculated for Alpine areas (see review in

Ballantyne and Harris, 1994), taking into account the areal expression of various processes involved in rockwall retreat leads to four conclusions: (1) post-glacial rockwall retreat has been generally very slow in the Arctic; (2) Holocene cliff recession has been largely dictated by chemical and biological weathering agents; (3) high retreat rates obtained in some Arctic locations are mainly associated with local bedrock conditions favouring frost shattering; and (4) the respective role of climate and glacier fluctuations in accelerating cliff recession at some periods during the Holocene is not clear, but their combination probably accounts for the fact that long-term post-glacial retreat rates may be much higher than present-day retreat rates.

Slowness of Holocene rockwall retreat and prevalence of biological and chemical processes

In the Arctic, the conspicuous effects of localized effectiveness of frost weathering in breaking down particularly susceptible rocks have led to an exaggeration of the importance of this process. One limestone erratic subject to frost bursting is immediately mentioned by field investigators (including the author), while the surrounding 200 intact gneiss erratics are ignored. Indeed, a close examination of Holocene erosion rates provided for Arctic areas leads one to question the academic view of freeze–thaw weathering as a key process responsible for rockwall retreat as well as for surface lowering.

In contrast with Alpine areas greatly affected by tectonic stresses and displaying densely jointed outcrops, extensive polar regions belong to shield areas developed in massive igneous and metamorphic rocks such as granite, gneiss, migmatite and syenite, whose susceptibility to frost weathering is negligible. Apart from episodic events (e.g. glacial surges apparently inducing stress relaxation mechanisms), such smooth rockwalls and outcrops mainly undergo a very slow chemical and biological disintegration resulting in average retreat rates of less than 100 mm ka^{-1}. This was previously demonstrated in studies carried out by Rapp (1960b) in Swedish Lappland and by Gray (1972) in the Yukon; in both regions, the overall Holocene cliff recession rarely exceeds 1–2 m.

The same conclusion is inferred from the present study of Spitsbergen amphibolite rockwalls: 95 per cent of their surface area is subject only to a very slow biogenic flaking due to lichen action, resulting in very low rockwall retreat rates (2 mm ka^{-1} on average), quite similar to the rates measured by Dahl (1967) and the present author (André, 1995) for post-glacial surface lowering of granite outcrops in North Scandinavia (1 mm ka^{-1}). Such estimates are also consistent with tentative rates proposed by Hall and Otte (1990) for Alaska where, during the last millennium, the slow flaking of granite nunatak walls (5 mm ka^{-1}) was caused by alternate phases of expansion and contraction of chasmoendolithic algae. Such low rates are of the same order of magnitude as rates of surface lowering due to solution processes affecting outcrops of limestone and dolomite, namely 3 mm ka^{-1} in Svalbard (Åkerman, 1983; André, 1993), 5 mm ka^{-1} in Swedish Lappland (André, 1996b), and 6 mm ka^{-1} in subarctic Quebec (Dionne and Michaud, 1986).

The local geomorphic impact of frost shattering due to specific bedrock conditions

In some Arctic locations, very high rockwall retreat rates of more than 1000 mm ka^{-1} are clearly connected with an unusually high density of structural discontinuities like joints and bedding planes. This is the case in northern Finland and arctic Canada where the overall Holocene cliff recession exceeds 10 m in stratified and/or densely fissured dolomitic limestone. In such cases, maximum rates are almost 1000 mm ka^{-1} in Finland (Söderman, 1980) and 1300 mm ka^{-1} on Ellesmere Island (Souchez, 1971). The post-glacial rockwall retreat even exceeds 15 m and possibly 20 m in West Greenland, where rates up to 2400 mm ka^{-1} have been tentatively estimated by Frich and Brandt (1985) for fractured basalt interbedded with clay layers. In the Norman Range area (District of Mackenzie, NW Canada), Smith (1973) infers, from an impressive series of talus-foot rock glaciers, an overall Holocene rockwall retreat of 60 m, equivalent to an average retreat rate of 5450 mm ka^{-1}. However, the inadequate chronological control makes this estimate questionable, even if geological conditions (folded, stratified limestone) are favourable for rapid cliff retreat.

In the Arctic in general, susceptibility to frost weathering appears to be associated with particular geological conditions, depending either on the mechanical behaviour of certain rock types or on the localized existence of fault and thrust lines within massive igneous rocks. This contrasts with Alpine areas that have been widely submitted to tectonic stresses, resulting in widespread fractured outcrops including igneous rocks (e.g. granite in the Mont-Blanc massif). In such areas, joint density, together with slope steepness and cliff height, account

for the high retreat rates reported by most researchers: 1000 mm ka^{-1} in gneiss and serpentine for the Austrian Alps (Poser, 1954), 1700 mm ka^{-1} in limestone for the Swiss Jura Mountains (Pancza, 1979), and up to 2500 and even 3000 mm ka^{-1} above active rock glaciers in the Swiss and French Alps (Barsch, 1977a,b; Francou, 1988) and on limestone in the Polish Tatra Mountains (Kotarba, 1972). Indeed, joint density appears as a prominent controlling factor in Alpine areas (Caine, 1983; Matsuoka and Uemoto, 1984; Evin, 1985) as well as in polar and subpolar areas (Gordon and Birnie, 1986; André, 1993).

The discontinuous history of rockwall retreat

In Arctic and Alpine areas, rockwall retreat rates estimated for the entire Holocene appear to be much higher than present-day rates inferred from slope monitoring and comparison of photographs. In central Spitsbergen, for instance, Rapp (1960a) observed the 'lack of agreement between present-day supply and the size of the cones' and reported rates of 0·02–0·2 mm a^{-1} for the period 1882–1954 but 0·35–0·5 mm a^{-1} for the last 10 000 years. Also, in the French Alps, Francou (1988) provides rates of 0·05–0·25 mm a^{-1} for recent times but 1 mm a^{-1} for the whole Holocene.

Such differences can be explained by climate and glacier fluctuations. In Svalbard, for instance, the last 10 000 years have obviously witnessed periods of intense geomorphic activity, resulting in the initiation of rock glacier movement during the Neoglacial stage, starting *c.* 3500 years BP, and in a high input to talus slopes at the end of the Little Ice Age (André, 1993). Such episodes are separated by quieter periods, like the Viking climatic optimum and the 20th century, that favour vegetation growth and rockwall stabilization. Field evidence for this intermittent rockwall retreat is provided by lichenometry in central Spitsbergen where, at the turn of the century, *Rhizocarpon* started colonizing amphibolite layers that had experienced active retreat during the Little Ice Age.

In some cases, the respective role of climate deterioration and glacier fluctuations in accelerating rockwall retreat is not very clear. The problem has been raised in the Scottish Highlands, where, to explain the very high retreat rates (1·5–4·0 mm a^{-1}) attributed to the Loch Lomond Stadial (*c.* 11–10 ka BP), Ballantyne and Kirkbride (1987) do not exclude the possible role of slope instability following ice sheet deglaciation in enhancing rockfall activity and protalus rampart formation. In west Spitsbergen, where the yield of huge boulders in an early phase of rock glacier formation might be an expression of post-glacial stress relaxation mechanisms (André, 1994), the important time-lag between deglaciation and rock glacier formation makes such a role questionable unless the geomorphic expression of stress relaxation mechanisms was delayed until enhanced by climatic deterioration.

CONCLUSIONS

Field measurements and lichenometric surveys carried out in Svalbard have yielded new estimates of post-glacial rockwall retreat that appear consistent with previous estimates for Arctic areas and can fruitfully be compared with results from Alpine areas. Four major conclusions can be emphasized.

(1) *The existence of a triple-rate rockwall retreat on Spitsbergen during the two last millennia*: 2 mm ka^{-1} (biogenic flaking), 100 mm ka^{-1} (frost shattering), *c.* 1000 mm ka^{-1} (post-glacial stress relaxation). Such a triple-rate evolution arises from the 15 investigated sites where rockwall retreat is clearly associated with one well-identified major process. It cannot be easily extrapolated to extensive areas because, in general, various weathering processes operate synergistically at the rockwall surface and cannot be separated.

(2) *The areal importance of slow and discrete chemical and biological actions that prevail on mechanical processes in massive igneous rocks which are widely represented in Precambrian shield areas.* Qualitative observations and tentative estimates from amphibolite rockwalls in Svalbard are consistent with evaluations provided by previous researchers (e.g. Rapp, 1960b; Gray, 1972; Eichler, 1981; Hall and Otte, 1990) and suggest that post-glacial rockwall retreat in massive igneous rocks does not often exceed 1–2 m in the Arctic. Such stability is demonstrated by the existence of slow-growing lichens, up to 2000 and even 5000 years old, that frequently mantle smooth and steep rockwalls.

(3) *The importance of bedrock conditions as a major control on rockwall retreat rates in the Arctic*: apart from specific glaciological conditions (surging episodes) that seem to accelerate rockwall retreat locally by inducing stress relaxation mechanisms, joint density accounts to a great extent for differences in retreat rates in various Arctic locations. In particular, the local susceptibility to frost weathering of fissured outcrops results in anomalously high retreat rates and conspicuous effects in Arctic landscapes. This probably explains the persistent overrating of the role of frost weathering mechanisms in Arctic areas that has been criticized for some time by various authors (Mortensen, 1928; Troll, 1944; Rapp, 1960b; Czeppe, 1964; Dixon *et al*., 1984; Hall and Otte, 1990).

(4) *The contrast between the general stability of Arctic rockwalls during the Holocene and the active post-glacial retreat (up to 30 m) reported from Alpine areas* (Caine, 1974; Barsch, 1977a,b; Francou, 1988; see also review in Ballantyne and Harris, 1994). This difference is mainly due, apart from the steepness of slopes and the greater vertical development of rockwalls, to the frequent occurrence of a dense joint pattern induced by tectonic stresses in Alpine environments.

Climatic conditions, such as the number of freeze–thaw cycles and the moisture availability, happen to influence the debris input, but their geomorphic impact is obviously governed by the network of cracks at various scales, particularly in hard igneous rocks (e.g. Terzaghi, 1962; Whalley *et al*., 1982; Walley, 1984; Douglas *et al*., 1991). For this reason, further research focusing on rockwall retreat problems in the Arctic should pay more attention to bedrock properties, often ‘forgotten, possibly because they were perceived as being self-evident’ (Twidale and Lageat, 1994, p. 319), especially in permafrost environments where climatic control has been systematically emphasized. Moreover, detailed studies should focus on chemical and biological weathering processes for these may be more important, if less conspicuous, components in polar geomorphology than frost mechanisms that only adorn landscapes with what could be regarded as ‘the icing on the cake’ (Thorn, 1992, p. 23).

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REFERENCES

Åckerman, H. J. 1983. ‘Notes on chemical weathering, Kapp Linné. Spitsbergen’, *Fourth International Permafrost Conference Proceedings*, 10–15.

André, M. F. 1990. ‘Geomorphic impact of spring avalanches in Northwest Spitsbergen (79°N)’, *Permafrost and Periglacial Processes*, **2**, 97–110.

André, M. F. 1993. *Les versants du Spitsberg – Approche géographique des paysages polaires*, doctoral thesis, University of Paris-Sorbonne, Presses Universitaires de Nancy, 361 pp.

André, M. F. 1994. ‘Rock glaciers in Svalbard – tentative dating and inferred long-term velocities’, *Geografiska Annaler*, **76A**(4), 235–245.

André, M. F. 1995. ‘Postglacial microweathering of granite *roches moutonnées* in Northern Scandinavia (Riksgränsen area, 68°N)’, in *Steepland Geomorphology*, Slaymaker, O. (Ed.), Wiley, Chichester, **7**, 103–127.

André, M. F. 1996a. ‘Geological control of slope processes in northwest Spitsbergen’, *Norsk Geografisk Tidsskrift*, **50**, 37–40.

André, M. F. 1996b. ‘Rock weathering rates in arctic and subarctic environments (Abisko Mts, Swedish Lappland), *Zeitschrift für Geomorphologie*, **40**(4), 499–517.

Ballantyne, C. K. and Harris, C. 1994. *The Periglaciation of Great Britain*, Cambridge University Press, Cambridge, 330 pp.

Ballantyne, C. K. and Kirkbride, M. P. 1987. 'Rockfall activity in upland Britain during the Loch Lomond stadial', *Geographical Journal*, **53**(1), 86–92.

Baranowski, S. 1977. The subpolar glaciers of Spitsbergen seen against the climate of this region, *Acta Universitatis Wratislaviensis,* **410**, 94 pp.

Barsch, D. 1977a. 'Eine Abschätzung von Schuttproduktion und Schuttransport im Bereich aktiver Blockgletscher der Schweizer Alpen', *Zeitschrift für Geomorphologie,* Suppl.-Bd **28**, 148–160.

Barsch, D. 1977b. 'Nature and importance of mass wasting by rock glaciers in alpine permafrost environments', *Earth Surface Processes and Landforms,* **2**, 231–245.

Cailleux, A. 1962. *Etudes de géologie au détroit de McMurdo (Antarctique),* Territoire des Terres australes et antarctiques françaises, CNFRA, **1**, 41 pp.

Caine, N. 1974. 'The geomorphic processes of the alpine environment' in Ives, J. D. and Barry, R. G. (Eds), *Arctic and Alpine Environments,* Methuen, 721–748.

Caine, N. 1983. *The Mountains of Northeastern Tasmania: A Study of Alpine Geomorphology,* Balkema, Rotterdam, 200 pp.

Calkin, P. E. and Ellis, J. M. 1980. 'A lichenometric dating curve and its application to Holocene glacier studies in the central Brooks Range, Alaska', *Arctic and Alpine Research,* **12**(3), 245–264.

Carson, M. A. and Kirkby, M. J. 1972. *Hillslope Form and Process,* Cambridge University Press, London, 475 pp.

Corbel, J. 1966. 'Datation au C 14 des terrasses marines de la baie du Roi', *Spitsberg 1964 – RCP 42–CNRS,* Audin, Lyon, 309–314.

Czeppe, Z. 1964. 'Exfoliation in a periglacial climate', *Geographia Polonica,* **2**, 5–10.

Dahl, R. 1967. 'Postglacial micro-weathering of bedrock surfaces in the Narvik district of Norway', *Geografiska Annaler*, **49**A, 155–166.

Dionne, J. C. and Michaud, Y. 1986. 'Note sur 1'altération chimique en milieu périglaciaire, Hudsonie, Québec subarctique', *Revue de Géomorphologie Dynamique,* **35**(3), 81–92.

Dixon, J. C., Thorn, C. E. and Darmody, R. G. 1984. 'Chemical weathering processes on the Vantage peak nunatak, Juneau icefield, southern Alaska', *Physical Geography,* **5**(2), 111–131.

Douglas, G. R., Whalley, W. B. and McGreevy, J. P. 1991. 'Rock properties as controls on free-face debris fall activity', *Permafrost and Periglacial Processes,* **2**, 311–319.

Eichler, H. 1981. 'Kleinformen der hocharktischen Verwitterung im Bereich der Oobloyah Bay, N-Ellesmere Island, N.W.T., Kanada – Formengenese und Prozesse', in Barsch, D. and King, L. (Eds), *Results of the Heidelberg Ellesmere Island Expedition,* Heidelberger geographische Arbeiten, **69**, 465–486.

Evin, M. 1985. 'Contribution à l'étude de la macrofissuration dans les parois situées à l'amont des glaciers rocheux des Alpes du Sud (France, Italie)', *Revue de Géomorphologie Dynamique,* **34**(1), 17–30.

Forman, S. L. and Miller, G. H. 1984. 'Time-dependent soil morphologies and pedogenic processes on raised beaches, Bröggerhalvöya, Spitsbergen, Svalbard Archipelago', *Arctic and Alpine Research,* **16**(4), 381–394.

Francou, B. 1988. *L'éboulisation en haute montagne,* doctoral thesis, University of Paris VII, 696 pp.

Frich, P. and Brandt, E. 1985. 'Holocene talus accumulation rates, and their influence on rock glacier growth. A case study from Igpik, Disko, West Greenland', *Geografisk Tidsskrift,* **85**, 32–43.

Gordon, J. E. and Birnie, R. V. 1986. 'Production and transfer of subaerially generated rock debris and resulting landforms on South Georgia: an introductory perspective', *British Antarctic Survey Bulletin,* **72**, 25–46.

Goudie, A. 1995. *The Changing Earth – Rates of Geomorphological Processes,* Blackwell, Oxford, 302 pp.

Gray, J. T. 1972. 'Debris accretion on talus slopes in the central Yukon Territory', in Slaymaker, H. O. and McPherson, H. J. (Eds), *Mountain Geomorphology: Geomorphological Processes in the Canadian Cordillera*, British Columbia Geographical Series no. **14**, 75–84.

Grosswald, M. G. 1967. 'Oledenenie Barencheva shelfa v pozdem Pleistocene i. Golotsemie, esnovye polozhenya' ('Glaciation of Barents continental shelf in late Pleistocene and Holocene ages: basic premise', *Mater. glyatsoil. issled., Chronika,* **13**.

Hall, K. and Otte, W. 1990. 'A note on biological weathering on nunataks of the Juneau icefield, Alaska', *Permafrost and Periglacial Processes,* **1**, 189–196.

Innes, J. L. 1985. 'Lichenometry', *Progress in Physical Geography,* **9**(2), 187–254.

Jahn, A. 1961. 'Quantitative analysis of some periglacial processes in Spitsbergen', *Zeszyty Naukowe,* ser. B, **5**, 3–55.

Kotarba, A. 1972. 'Comparison of physical weathering and chemical denudation in the Polish Tatra Mts', in *Processus Périglaciaires Étudiés sur le Terrain*, International Symposium held in Liège and Caen (1971), 205–216.

Liestøl, O. 1969. 'Glacier surges in West Spitsbergen', *Canadian Journal of Earth Sciences,* **6**, 895–897.

Lock, W. W., Andrews, J. T. and Webber, P. J. 1979. *A Manual for Lichenometry,* BGRG Technical Bulletin, **26**, 48 pp.

Matsuoka, N. and Uemoto, S. 1984. 'Lithological control on ridge topography in alpine region of the Japanese Alps, *Geographical Review of Japan,* **57A**, 263–281.

Miller, G. H. and Andrews, J. T. 1972. 'Quarternary history of northern Cumberland peninsula, East Baffin Island, N.W.T., Canada. Part VI: preliminary lichen growth curve for *Rhizocarpon geographicum', Geological Society of America Bulletin,* **83**, 1133–1138.

Mortensen, H. 1928. 'Über die klimatischen Verhältnisse des Eisfjordgebietes', *Chemie der Erde*, **3**(3–4).

Pancza, A. 1970. *Contribution à l'étude des formations périglaciaires dans le Jura,* doctoral thesis, University of Neuchâtel, 187 pp.

Poser, H. 1954. 'Die Periglazial-Erscheinungen in der Umgebung der Gletscher des Zemmgrundes (Zillertaler Alpen)', *Götting. Geogr. Abhandl.,* **15**, 125–180.

Rapp, A. 1960a. *Talus slopes and mountain walls at Tempelfjorden, Spitsbergen,* thesis, Meddelanden Uppsala Universitets Geografiska Institution, **55A**, 96 pp.

Rapp, A. 1960b. *Recent development of mountain slopes in Kärkevagge and surroundings, Northern Scandinavia,* thesis, Meddelanden Uppsala Universitets Geografiska Institution, **158A**, 71–200.

Rapp, A. and Rudberg, S. 1964. 'Studies on periglacial phenomena in Scandinavia 1960–1963', *Biuletyn Peryglacjalny,* **14**, 79–81.

Salvigsen, O. 1977. 'Radiocarbon datings and the extension of the Weichselian ice-sheet in Svalbard', *Norsk Polarinstitutt Arbok 1976*, 209–224.

Salvigsen, O. 1978. 'Holocene emergence and finds of pumice, whalebones, and driftwood at Svartknausflya, Nordaustlandet', *Norsk Polarinstitutt 1977,* 217–228.

Smith, H. T. U. 1973. ‘Photogeologic study of periglacial talus glaciers in Northwestern Canada’, *Geografiska Annaler,* **55A**, 69–84.

Söderman, G. 1980. ‘Slope processes in cold environments of northern Finland’, *Fennia,* **158**(2), 1–186.

Souchez, R. 1971. ‘Rate of frost-shattering and slope development in dolomitic limestone, southwestern Ellesmere Island (Arctic Canada), *Quaternaria,* **XIV**, 21.

Terzaghi, K. 1962. ‘Stability of steep slopes on hard unweathered rock’, *Géotechnique*, **12**, 251–270.

Thorn, C. E. 1992. ‘Periglacial geomorphology: What? Where? When?’, in Dixon, J. C. and Abrahams, A. D. (Eds), *Periglacial Geomorphology,* Wiley, Chichester, 1–30.

Troll, C. 1944. ‘Strukturboden, Solifluktion and Frostklimate der Erde’, *Geologische Rundschau,* **XXXIV**, 545–694.

Twidale, R. and Lageat, Y. 1994. ‘Climatic geomorphology: a critique’, *Progress in Physical Geography,* **18**(3), 319–334.

Werner, A. 1990. ‘Lichen growth rates for the northwest coast of Spitsbergen, Svalbard’, *Arctic and Alpine Research,* **20**, 292–298.

Whalley, W. B. 1984. ‘Rockfalls’, in Brunsden, D. and Prior, D. B. (Eds), *Slope Instability,* Wiley, Chichester, **7**, 217–256.

Whalley, W. B., Douglas, G. R. and McGreevy, J. P. 1982. ‘Crack propagation and associated weathering in igneous rocks’, *Zeitschrift für Geomorphologie,* **26**(1), 33–53.